Unident: Providing Impact Sensations on Handheld Objects via High-Speed Change of the Rotational Inertia

Shuntaro Shimizu*
The University of Tokyo

Takeru Hashimoto
The University of Tokyo

Shigeo Yoshida
The University of Tokyo
JST, PRESTO

Reo Matsumura
karakuri products Inc.
The University of Tokyo

Takuji Narumi
The University of Tokyo
JST, PRESTO

Hideaki Kuzuoka
The University of Tokyo

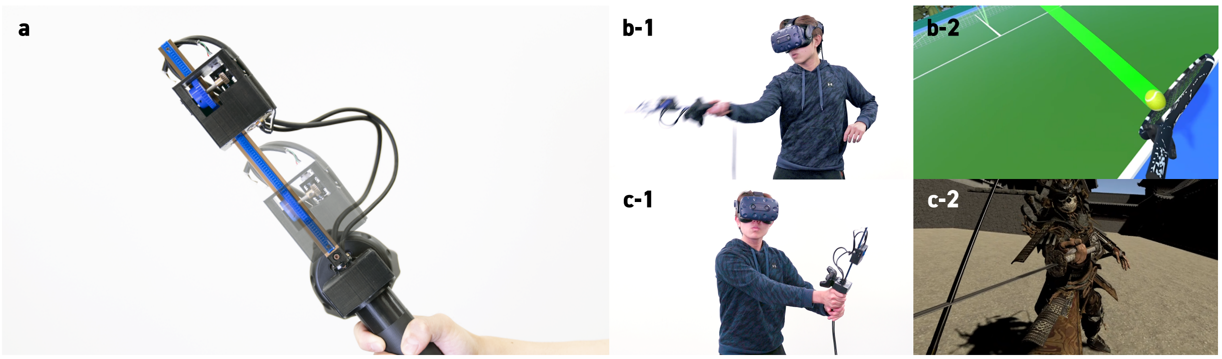

Figure 1: a: Unident is a handheld proxy capable of providing users with impact sensations by changing its rotational inertia while users are swinging it. Unident has a weight module that can move at a speed of 1 mm/ms and can change its rotational inertia by a factor of approximately four in 150 ms. Users can perceive an impact sensation with various magnitudes depending on the speed of a tennis ball (b-1, b-2) or the power of the sword-wielding enemy (c-1, c-2).

ABSTRACT

Several virtual reality (VR) proxies have been developed that can emulate impact sensations by generating actual forces on the hand. Although these proxies contribute to increasing the reality of VR, they still have some limitations, such as high latency, high power consumption, and low frequency to provide impact sensations. To overcome these limitations, we first propose a method to provide an impact sensation without actual force generation by quickly changing the rotational inertia of a handheld proxy while users are swinging it. Then, we developed *Unident*, a handheld proxy capable of changing its rotational inertia by moving a weight along one axis at a high speed. Two experiments were conducted to evaluate the ability of Unident to provide users with impact sensations. In the first experiment, we demonstrate that Unident can physically provide an impact sensation applied to a handheld object by analyzing the pressure on the user's palm. The second experiment shows that Unident can provide an impact sensation with various magnitudes depending on the amount of rotational inertia to be changed. Finally, we present an application that can be enabled by Unident.

Index Terms: Human-centered computing—Human computer interaction—Interaction devices—Haptic devices;

1 INTRODUCTION

Haptic sensation plays an important role in virtual reality (VR) experiences. It allows the user to understand the physical properties of virtual objects and receive force feedback in a virtual environment (VE). Currently, various handheld controllers, such as VIVE Controller[1] and Oculus Touch[2], are widely used as haptic feedback proxies in VR experiences. These controllers are typically equipped with vibrators, allowing people to perceive haptic cues in a VE. However, since the expressiveness of the haptic experience with vibration is limited, which often causes discrepancies between visual and haptic information in VEs.

Researchers have developed several proxies to provide users with sophisticated haptic feedback to make VR experiences more realistic. Some proxies are capable of rendering an object's physical properties, such as the shape [23,26,35], weight [10,36], weight distribution [8,22], elasticity [19,28], and temperature [4,32]. Other proxies provide force feedback, such as impact forces [11, 15, 33], tugging forces [3, 9], and reaction forces [1, 13, 29] by generating an actual force or torque on them.

While previous works have succeeded in representing impact sensations using air-based mechanisms [11, 25], reaction wheels [2, 12], control moment gyroscopes (CMG) [31, 33], and elastic bands [27,29], they have some limitations such as the high latency, high power consumption, and low frequency for providing impact sensations. A high latency causes a delay between the haptic and visual stimuli and degrades the realism of VR experiences. High power consumption arises from the requirement to apply large voltages to the jet propellers or to keep the flywheels spinning at a high speed to generate forces. Proxies with the limitation of a low frequency for providing impact sensations cannot be used for applications that involve multiple impacts in a short period of time, e.g., tennis, kendo (Japanese-style fencing), etc.

To overcome these limitations, we propose a method to provide impact sensations by quickly changing the rotational inertia of a handheld proxy while users are swinging it. Considering how we physically perceive impact forces, we expect that to provide an impact sensation, it is not necessary to generate an actual force, but

*e-mail: s_shimizu@cyber.t.u-tokyo.ac.jp

[1]https://www.vive.com/us/accessory/controller
[2]https://www.oculus.com/quest-2

2642-5254/21/$31.00 ©2021 IEEE
DOI 10.1109/VR50410.2021.00021

2021 IEEE Virtual Reality and 3D User Interfaces (VR) | 978-1-6654-1838-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/VR50410.2021.00021

only to rapidly change the rotational inertia of the handheld object. Because our method only changes the rotational inertia, it requires less power than conventional proxies with actual force generation. Moreover, if it is possible to achieve rapid changes in the rotational inertia, impact sensations can be provided at a high frequency.

In this study, we first derived a kinetic model of how we perceive an impact sensation through a handheld object based on the rotational equation of motion. We then developed *Unident*, a handheld proxy capable of changing the rotational inertia by moving its weight along one axis at a high speed (Fig. 1). Unident can increase its rotational inertia by a factor of approximately four in 150 ms. Additionally, we expect that Unident can also render the different sizes of handheld objects, because the previous studies have reported that this can be achieved by changing the rotational inertia of the handheld proxy [8, 22, 36, 37].

The four main contributions of this study are as follows:

1. A novel approach was proposed for providing an impact sensation to a handheld object by changing its rotational inertia while the user swings it, based on the kinetic model of how we perceive an impact sensation.

2. Unident, which is capable of changing the rotational inertia by moving a weight along one axis at a high speed was designed and implemented.

3. Unident's ability to provide an impact sensation based on the kinetic model was evaluated through two experiments. Unident succeeded in making users perceive impact sensations with different magnitudes and enhanced the realism of the haptic experience in VR.

4. A user study was performed involving a VR application, and the haptic experience was compared between Unident and a conventional controller with vibration. The results indicated that Unident enhanced the realism of the VR experience compared to the conventional controller and could render the different sizes of handheld objects based on the initial position of the weight.

2 Related Work

Unident builds upon the previous studies on haptic proxies, particularly proxies with actual force generation, proxies with haptic feedback design based on the kinetic model and proxies that change their rotational inertia.

Haptic Proxies with Actual Force Generation

Several mechanisms have been developed to generate forces or torques to provide users with active haptic feedback.

Thor's Hammer [9], Wind-Blaster [11], and LevioPole [21] generate linear forces by actuating jet propellers. Because these proxies can continuously generate large forces of up to 4 N [9], they are employed to provide users with tugging forces, reaction forces and gravitational forces. However, the aforementioned mechanisms have three main limitations: a high latency, high power consumption, and loud noise. It takes approximately 300 ms to generate the target force from a stationary state [9], which may not be appropriate for haptic scenarios that require instantaneous or rapid feedback. When the proxy generates a force of 4 N, it requires a large amount of power (204.7 W) [9]. It creates a substantial amount of noise ranging from 41 to 93.5 dB [9–11], which affects the immersion.

Virtual Chanbara [12], GyroCube [20], GyroCubeSensuous [17], and the proxy developed by Ando et al. [2] generate torques by changing the angular momentum of the attached flywheels. Because this mechanism can generate a large torque with a low latency [2], it can provide users with an impact force. However, because the flywheel must be kept spinning at a high speed to generate a large torque, this mechanism consumes a large amount of power. The frequency for providing an impact sensation is low, because it takes some time to rotate the flywheel at a high speed from its static state. Additionally, users are provided with an undesirable torque because of moment components orthogonal to the desired torque output arising from the acceleration of the flywheel [31].

A double-gimbal CMG [3, 33, 34] can generate torques by tilting the rotation axis of the flywheel. Compared with the angular momentum changing method, this mechanism can generate a larger torque with a smaller proxy, but it also generates an undesirable torque [31]. Walker et al. [31] developed two double-gimbal CMGs and successfully eliminated undesirable torques. However, these gimbal mechanisms consume a large amount of power because they require continuous rotation of the flywheels at high speed to generate a torque. Additionally, the complex control is needed to provide a desirable torques at high frequencies because the provided torque is sometimes limited by the orientation of the flywheels.

ElasticVR [29] and ElastImpact [27] can generate resistive forces and impact forces using elastic bands. These mechanisms can provide resitive forces without delay by utilizing the elasticity of the bands. However, they cannot provide impact forces at high frequencies, because they need some time to wind up the elastic bands.

The main difference between Unident and these proxies is that Unident does not generate actual forces or torques but changes its rotational inertia to provide an impact sensation. This feature makes the power consumption lower than those of the foregoing proxies. Moreover, Unident can provide impact sensations at high frequencies without providing an undesirable force feedback, because it can easily return to its initial state after providing an impact.

Haptic Feedback Design Based on Kinetic Model

Researchers have proposed several methods for indirectly providing desirable haptic sensations to users based on a kinetic model. Minamizawa et al. [16] indirectly presented the sensation of holding an object with various weights. Their method involved modeling the forces generated between an object and the fingers when an object was held by the fingers, and a shearing force was applied to the fingers. They also showed that the method could physically represent the sensation by analyzing the pressure on the fingers. Aero-plane [10] can render weight motion on a handheld two-dimensional plane. In this study, the researchers first simulated the gravity on a handheld plane when the weight moved and then represented it via force feedback with two jet propellers. They reported that users could perceive the weight movement precisely and that the method improved the realism and immersion.

Both the proposed method and the abovementioned methods aim to indirectly provide the desired haptic sensations to users based on their kinetic model. To provide impact sensations via high-speed changes in the rotational inertia, we first derive the kinetic model of how we perceive an impact sensation through a handheld object. We then expect to be able to physically represent an impact sensation by actuating Unident based on our model.

Haptic Proxies Changing Their Rotational Inertia

Because the size and length of a handheld object are perceived according to its rotational inertia [24, 30], several proxies have been developed to render various sizes and lengths by controlling their rotational inertia.

For example, Shifty [36] and Transcalibur [22] have moving weights and can change their rotational inertia by changing the positions of the weights. Drag:on [37] uses foldable thin surfaces, and ShapeSense [14] uses moving plates instead of a weight to not only control the rotational inertia to render the size or shape of a handheld object, but also emulate the air resistance.

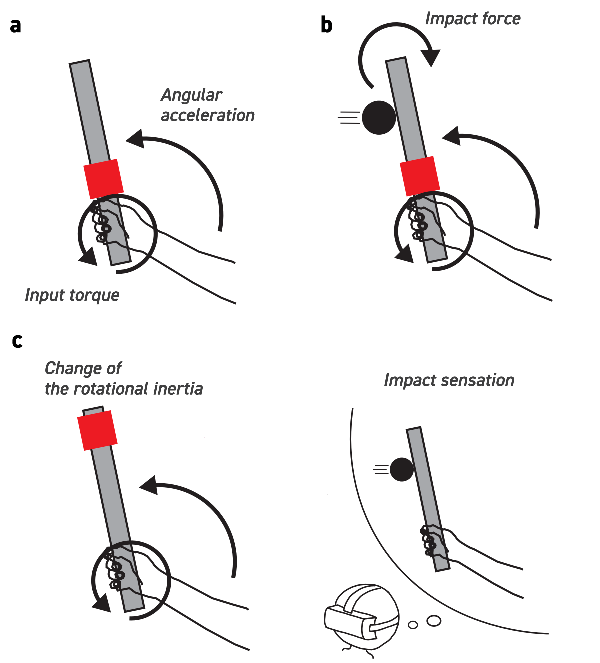

Figure 2: Proposed kinetic model. The user first inputs a torque to a handheld object and swings it (a). He/she then perceives an impact sensation based on instantaneous changes in motion caused by an impact force (b). Unident provides an impact sensation by rapidly changing its rotational inertia while he/she is swinging it (c).

Unident also changes the rotational inertia by moving the weight. The difference between the aforementioned proxies and Unident is that our method provides an impact sensation via rapid movement of the weight based on the kinetic model of how we perceive an impact sensation derived from the rotational equation of motion (see Section 3 for details). Moreover, we consider that our method based on the kinetic model extends the expressiveness of these weight-shifting proxies.

3 Kinetic Model of Impact Sensation

In this section, we describe the kinetic model of how we perceive an impact sensation on a handheld object based on the rotational equation of motion. We then explain how Unident can provide users with an impact sensation by changing its rotational inertia at a high speed.

First, as in Equation 1, we can describe the motion of a handheld object being swung according to the rotational equation of motion (Fig. 2(a)):

$$I\ddot{\theta} = T_h \tag{1}$$

where I represents the rotational inertia of the handheld object around the holding point, $\ddot{\theta}$ represents the angular acceleration, and T_h represents the user's input torque to the handheld object. For simplicity, the effect of the gravitational moment is ignored. When an impact force, T_e is applied to the handheld object during this motion, Equation 1 changes to Equation 2 instantly (Fig. 2(b)).

$$I\ddot{\theta} = T_h - T_e \tag{2}$$

We assume that we perceive an impact sensation on a handheld object through this mechanism.

When Unident changes its rotational inertia at a high speed, Equation 1 instantly changes to Equation 3.

$$(I + \Delta I)\ddot{\theta} = T_h \tag{3}$$

Here, ΔI represents the change in the rotational inertia of the handheld object in the real environment. If the appearance of the handheld object is not changed in the VE, the user is expected to perceive this dynamics as follows:

$$I\ddot{\theta} = T_h - \Delta I\ddot{\theta} \tag{4}$$

By providing the visual information about the impact force on the handheld object, the user is expected to perceive $-\Delta I\ddot{\theta}$ as an impact sensation in the same way as Equation 2. Although it is known that we can render materials that collide with a handheld object via high-frequency vibrations [18], our main objective is to emulate an impact force based on Equation 4, and not the materials. In the first experiment, we checked whether users perceived an impact sensation, as indicated by Equation 4. We expect that it is possible to provide impact sensations with various magnitudes by designing the change in the rotational inertia, ΔI; this was investigated in the second experiment.

4 Design and Implementation of Unident

We describe the hardware and software specifications of Unident in this section. Fig. 3 shows the mechanical design of Unident.

The design of Unident was inspired by Shifty [36] and Transcalibur [22]. The major difference between Unident and these proxies is the higher speed for moving the weight module to change the rotational inertia. To achieve the quick movement of the weight module, Unident has a high-torque motor and is designed to have substantial rigidity to withstand the output load. Additionally, the stop position of the weight module can be controlled within an error of 15 mm via proportional-integral-derivative (PID) control even when the weight module is moving at a high speed. The design rationale of Unident is as follows:

1. Fast movement of the weight module: According to our model, Unident must change its rotational inertia within the amount of time taken for the impact force to be actually applied. To approach to this ideal condition, we determine the motor specifications and gear ratios that maximize the speed of the weight module. Additionally, the proxy requires to be substantially rigid to withstand the output load.

2. Wide control range of the rotational inertia: Because the control range of the rotational inertia is directly related to the magnitude of the impact sensation that can be provided, we make the movement range of the weight module as wide as possible.

3. Non-backdrivability: A non-backdrivable mechanism, i.e., a worm gear, is used to prevent the weight module from moving under external forces or the gravity.

Hardware

Unident consists of a 3D-printed grip, a weight module made of polylactic acid (PLA), and a 3 mm thick aluminum plate rail. The dimensions of the proxy are $60 \times 424 \times 120\,\mathrm{mm}^3$, and its total weight is 270 g. The weight module consists of a Mabuchi DC Motor (RS-380PH[3]), a worm gear with a 10:1 reduction ratio, a spur gear, and a Pololu magnetic encoder[4]. The dimensions of the weight module are $58 \times 70 \times 35\,\mathrm{mm}^3$, and its weight is 160 g. The output of the motor is transmitted through the worm gear to the spur gear, and the weight moves on a rack fixed on the rail. This mechanism provides the non-backdrivable feature; i.e., the weight module is not moved by external forces or the gravity. Unident can change the rotational inertia by up to $8.4\mathrm{g}\cdot\mathrm{m}^2$ around the holding point.

[3] https://product.mabuchi-motor.co.jp/detail.html?id=98
[4] https://www.pololu.com/product/2598

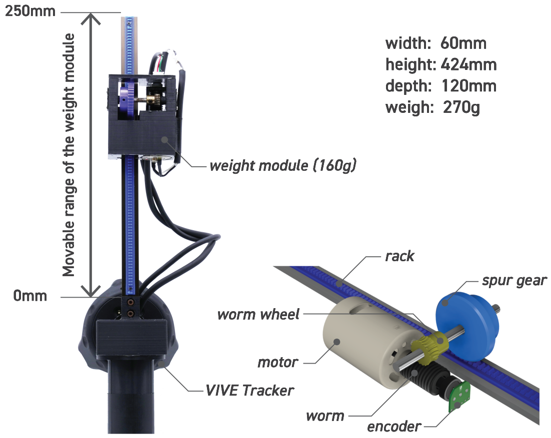

Figure 3: Detailed mechanical design of Unident. The weight module moves along the rack and is actuated by the motor through the worm gear. It can move at 1 mm/ms.

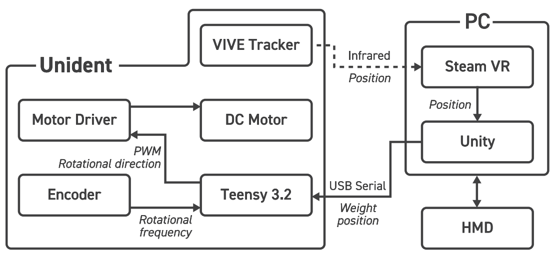

Figure 4: System diagram of Unident.

Fig. 4 shows the system diagram of Unident. Regarding the circuit components, we use Teensy 3.2[5] as a microcomputer and MDD10A[6] as a motor driver. The proxy consumes a maximum voltage and current of 10 V / 5 A when the weight module is moving. VIVE Tracker[7] attached to Unident tracks the position and the orientation of the proxy, and this information are sent to applications via Steam VR[8].

Software

The firmware for motor control is written in C++ for Arduino. We use a PID controller to accurately control the speed of the weight module. The position of the weight module is measured by the encoder, and the motor stops when the weight module is within ± 15 mm of the target position. This threshold is determined by considering the delay between the transmission of the signal to stop the motor and the actual stoppage. The target speed of the weight module is set to 1 mm/ms, and the weight module can be moved to from one end of the rail to the other at approximately 150 ms. This allows Unident to provide an impact sensation and return to the initial state in approximately 300 ms.

We used Unity[9] to develop VR applications for the experiments and the user study. These applications send the commands to control Unident via serial communication by USB.

[5]https://www.sparkfun.com/products/13736
[6]https://www.cytron.io/p-10amp-5v-30v-dc-motor-driver-2-channels
[7]https://www.vive.com/us/accessory/vive-tracker
[8]https://store.steampowered.com
[9]https://unity.com

5 Experiment 1: Ability to Provide Impact Sensation

The objective of this experiment was to determine whether Unident can provide an impact sensation according to our model. This proposition was discussed based on the physical evaluation of the pressure on a user's palm when the user hit a real/virtual ball and his/her subjective evaluations of the impact sensation (i.e., whether it felt like hitting a ball). The methods used to measure and discuss the pressure recordings on the user's palm were based on a previous study [16].

Participants

For this study, 12 paid participants (11 males and 1 female) aged 19 to 25 years (mean: 21.7; standard deviation (SD): 1.67) were recruited. Two participants were left-handed, while the other participants were right-handed. Each participant received an Amazon gift card worth approximately 9 USD (￥1,000) for their participation.

Design and Setup

There were three conditions in this experiment: hitting a real ball, hitting a virtual ball without haptic feedback, and hitting a virtual ball with haptic feedback.

The VE setup is shown in Fig. 5(a-1, a-2). The participants wore a head-mounted display (HMD), HTC VIVE Pro[10], and hit a virtual rigid ball with Unident held in their right hand. We instructed the participants to follow a translucent virtual object (guide object) that guided their swing motion. The purpose of this instruction was to eliminate perceptual errors caused by the differences in the angular acceleration among the participants. Considering Equation 4, the angular acceleration with which the participants swung the handheld object was expected to affect the impact sensation.

When the participants swung Unident, the weight module moved to the target position. We did not return the weight module to its initial position to compare the pressure without the noise that might occur when the weight module returns. The time to send of the command for motor actuation was set to 150 ms before the collision to stop the weight module when the ball and the handheld object collided. In the condition with haptic feedback, the target position at which the weight module stopped was 150 mm. In the condition without haptic feedback, the weight module did not move; thus, the target position was set to 0 mm.

The setup of the real environment is shown in Fig. 5(b). The participants hit a real ball suspended by a string by swinging a proxy in their right hand. We instructed the participants to swing the proxy at a speed identical to that in the VE (the greatest extent possible) to eliminate errors in the pressures on their palms due to differences in the swing speed. The proxy had the same weight and center of gravity as Unident (with the weight module is in the initial position). The ball was made of plastic and weighed 50 g.

While the participants swung Unident, we measured the pressure on the palm using two force sensitive resistors (SEN-09375 [11]). We placed the resistors at the base of the index finger and at the middle of the little finger of the right hand, because the highest pressure was applied at these two points when the ball was hit with the proxy (Fig. 6). We set the pressure-sampling rate to 100 Hz, referring to a previous study [5].

Procedure

The experiment was conducted using the following procedure, and the time for each participant was approximately 30 min.

1. Instructions regarding the experiment
2. Practice for tasks in the VE

[10]https://www.vive.com/jp/product/vive-pro-full-kit
[11]https://www.sparkfun.com/products/9375

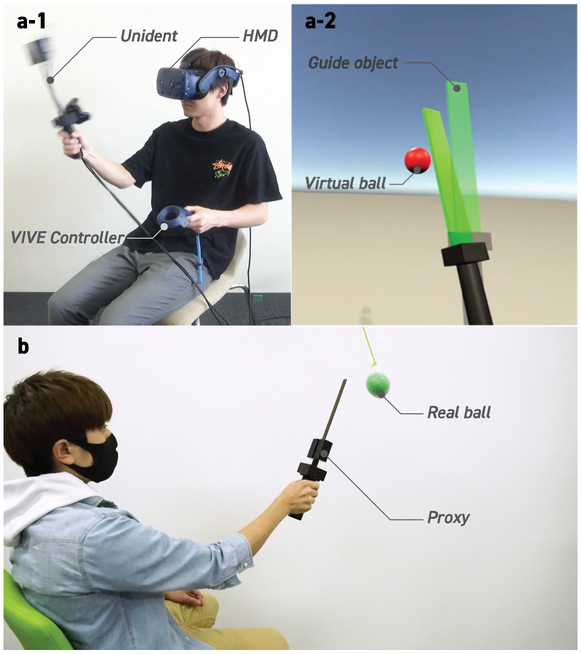

Figure 5: Experimental setup. Participants wore an HMD and hit a virtual ball with Unident, and the weight module moved to the target position while swinging it (a-1, a-2). Participants hit a real ball with a proxy, which had the same weight and center of gravity as Unident (b).

3. Tasks in the VE
4. Tasks in the real environment
5. Questionnaire

During steps 2 and 3, the participants wore the HMD and held Unident in their right hand and VIVE Controller in their left hand. In step 2, the participants practiced hitting a virtual ball by following the guide object. Then, the participants learned how to answer the questionnaire using the VIVE Controller. In step 3, participants hit a virtual ball. This task was performed five times for each condition. Two conditions in the VE were applied in a random order to eliminate the order effect. At the end of each condition, the participants answered the question, “Did you feel like you actually hit a ball?” on a 7-point Likert scale.

Next, the participants removed the HMD and performed the task

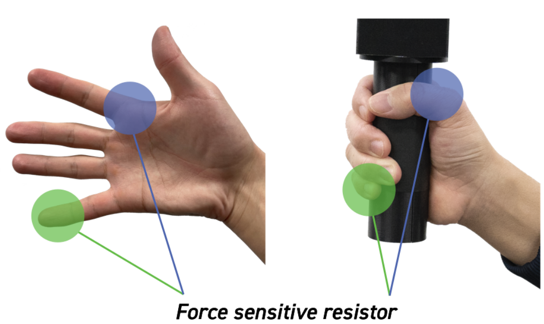

Figure 6: Force sensitive resistors were placed at the base of the index finger and at the middle of the little finger to measure the pressure on the participant’s palm.

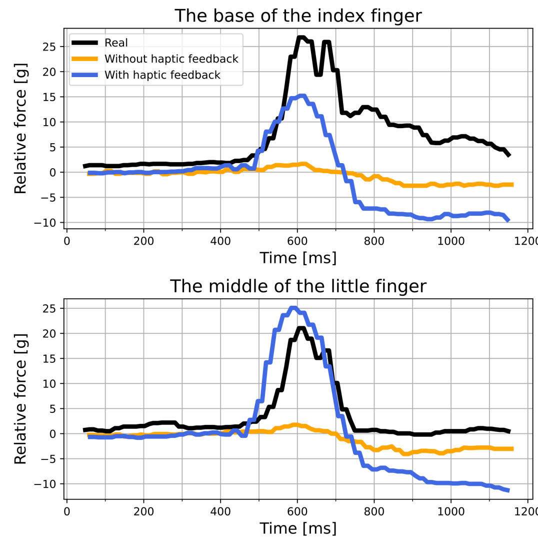

Figure 7: Pressure recordings for each condition: hitting the real ball (black), hitting the virtual ball with haptic feedback (blue), and hitting the virtual ball without haptic feedback (orange).

of hitting a real ball. This task was performed five times for each condition, similar to the VE task.

Each condition was applied once. Subsequently, the participants answered the open-ended questionnaire, “What did you feel or notice in this experiment?”

Results and Discussion

Fig. 7 shows the pressure recordings for three conditions: hitting the real ball, hitting the virtual ball with haptic feedback, and hitting the virtual ball without haptic feedback. The pressure indicated the relative value to the pressure in a static holding. We recorded the timing of hitting the virtual ball with and without haptic feedback. We then adjusted the timeline of the black line (real) and the other lines (with and without haptic feedback) to match the pressure peak of the black line and the hitting timing of the virtual ball. Under the condition where participants hit the real ball, an impulsive increase in the pressure occurred as the ball collided with the handheld object. In the VE, we observed a similar impulsive increase in the pressure with haptic feedback, although the increase was a little slower than when hitting the real ball. However, it was not detected when hitting a virtual ball without haptic feedback. Furthermore, the pressure rise time was approximately 250 ms for both hitting the real ball and hitting the virtual ball with haptic feedback. After hitting the virtual ball with haptic feedback, the pressure was lower than when hitting the real ball. However, this difference was not expected to affect an impact sensation, because no participants reported about this difference.

Fig. 8 shows the differences of pressure recordings between hitting the virtual ball with/without haptic feedback and hitting the real ball. Lower values indicate that the haptic feedback physically represent an impact sensation more realistically. The values represent the average of 60 points (12 participants $\times$ 5 times), and the error bars represent the standard error. We used dynamic time warping to calculate the differences between the pressure recordings. Then, the differences were calculated using only the recordings at 150 ms before and after the time when the ball and the handheld object collided. The reason for using this process was to focus only on the pressure recording when the ball was hit. A paired t-test of the data revealed a significant difference at both the base of the index finger ($p = 0.0038$) and the middle of the little finger ($p = 0.0061$). These

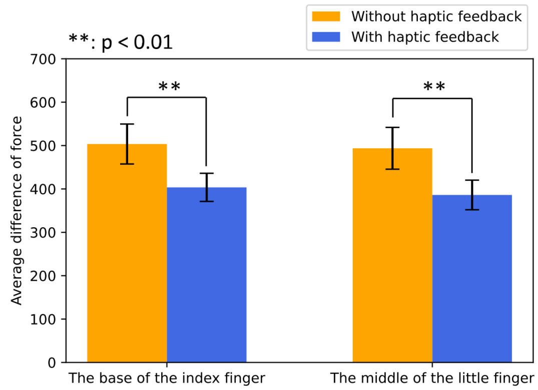

Figure 8: Differences of the pressure recordings between hitting the virtual ball with (blue)/without (orange) haptic feedback and hitting the real ball. Lower values indicate that the haptic feedback physically represented an impact sensation more realistically. The values represent the average of 60 points, and the error bars represent the standard error.

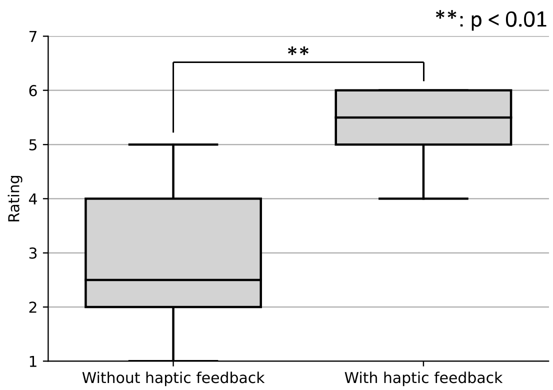

Figure 9: Participants' subjective evaluations for the questionnaire, "Did you feel like you actually hit a ball?".

results for the pressure on the user's palm suggest that Unident can physically provide an impact sensation on a handheld object.

Fig. 9 shows the participants' responses to the question, "Did you feel like you actually hit a ball?". Wilcoxon signed-rank tests indicated the significant difference in the responses between with and without haptic feedback ($W = 0, p = 0.0005$). The results suggest that the haptic feedback using Unident made the users feel more like hitting a real ball compared with the case without haptic feedback.

Overall, the results of the experiment indicate that Unident can physically provide an impact sensation on a handheld object and improve the realism of a VR experience.

6 Experiment 2: Magnitude Range of Impact Sensation

According to the kinetic model introduced in Section 3, we expect that Unident can provide an impact sensation with various magnitudes depending on the amount of the rotational inertia to be changed. The purpose of this experiment is to investigate the magnitude range of an impact sensation. The experimental method of having participants adjust visual stimuli depending on haptic feedback is designed based on a previous study [22].

Participants

For this study, 8 paid participants (all males) aged 21 to 24 years (mean: 23.3; SD: 1.16) were recruited. All the participants were right-handed. Each participant received an Amazon gift card worth approximately 9 USD (¥1,000) for their participation in the experiment.

Design and Setup

The setup of this experiment was identical to that of the first experiment (Fig. 5(a-1, a-2)). The participants hit a virtual ball by swinging Unident with their right hand. The participants were then instructed to follow the guide object while swinging Unident. The purpose of this instruction was to eliminate perceptual errors caused by the differences in the angular acceleration among the participants. Considering Equation 4, the angular acceleration with which the participants swung the handheld object was expected to affect the magnitude of the impact sensation. When the participants swung Unident, the weight module moved to the target position. The time to send the command for motor actuation was such that the weight module would stop when the ball and the handheld object collided.

There were six conditions for the position where the weight module was stopped: 0, 30, 60, 90, 120, and 150 mm. Under each condition, after hitting a virtual ball, the participants visually adjusted the size of the ball depending on the magnitude of the impact sensation they perceived. We instructed the participants to input a larger size if they perceived stronger haptic feedback.

Procedure

The experiment was conducted using the following procedure, and the time for each participant was approximately 45 min.

1. Instructions regarding the experiment
2. Practice for tasks in the VE
3. Tasks under the control condition
4. Tasks under the experimental condition
5. Questionnaire

During steps 2 and 3, the participants wore an HMD (HTC VIVE Pro) and held Unident in their right hand and a VIVE Controller in their left hand.

In step 2, the participants practiced hitting a virtual ball by following the guide object. Additionally, they learned to visually adjust the ball size (Fig. 10), as well as the maximum and minimum ball sizes that they could input (270 mm and 30 mm in diameter, respectively).

In step 3, the participants performed the task under the control condition to check the reference magnitude of the impact sensation and the reference size of the ball. The position where the weight module stopped in the control condition was 75 mm, and the reference size of the ball was 90 mm in diameter.

The participants then hit the virtual ball under the experimental condition and visually adjusted the ball size relative to the reference magnitude of the impact sensation. They repeatedly hit the virtual ball of the input size and adjusted the ball size, and finished the trial when they determined that the ball size was the most appropriate. Six experimental conditions were applied in a random order to eliminate the order effect. Each condition was applied twice.

Finally, the participants answered two open-ended questions: "What did you feel or notice in this experiment?" and "What kind of applications do you think this system can be used for?".

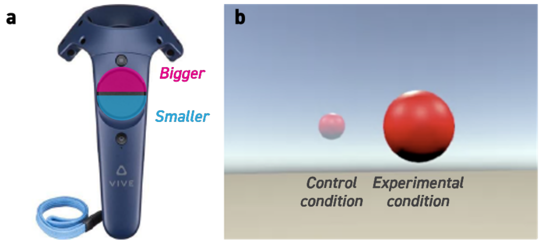

Figure 10: Participants visually manipulated the ball size using VIVE Controller (a). The ball in the control condition is showed next to the ball manipulated by the participants (b).

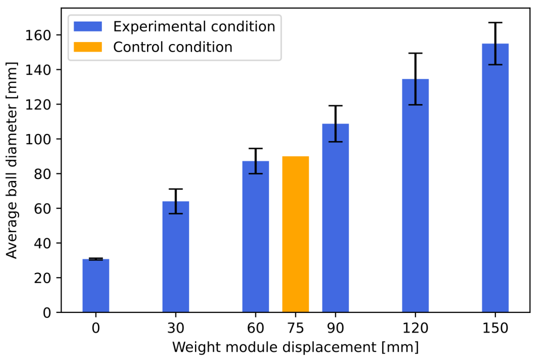

Figure 11: Position where the weight module stopped and the average of the ball size inputted under each condition. The error bars indicate the standard error.

Results and Discussion

Fig. 11 presents the average of the ball size estimated under each condition. As shown, the magnitude of the perceived impact sensation depended on the position of the weight module. The correlation coefficient between these two values was approximately 0.74 ($R^2 = 0.54$), indicating a positive correlation. This relationship is consistent with Equation 4, because the rotational inertia of Unident increases as the position of the weight module moves up toward the tip.

We developed a computational perception model (Equation 5) relating the magnitudes of the impact sensations to the position where the weight module stops based on the previous studies [8,22] by utilizing data from this experiment.

$$T_s = 0.65 \times \Delta I + 0.31 \tag{5}$$

Here, T_s represents the magnitude of the impact sensations, and ΔI represents the amount of rotational inertia to be changed. Note that these values were normalized with the values of the standard stimulus. Equation 5 suggests that Unident can provide an impact sensation of approximately 0.5-2.0 times stronger than the standard stimulus because ΔI is between 0 and 2.4.

The participants commented that Unident could be used not only for ball-hitting sports (e.g., tennis, baseball, and cricket) but also for fighting-based games that use a handheld object (e.g., kendo).

7 Application

We developed an application to evaluate the performance of Unident for providing impact sensations in an actual VR experience. We can investigate whether Unident can provide impact sensations even when swinging at different speeds because the user could freely swing Unident in this user study. This application was developed considering the participants' answers in the second experiment to the question "What kind of applications do you think this system can be used for?".

Figure 12: User with Unident plays tennis with a non-player character (NPC). When the user's racket comes in contact with the ball, Unident changes its rotational inertia by moving the weight module. Then, the user perceives an impact sensation with the haptic feedback of Unident.

In the application, a user plays tennis with a non-player character (NPC) (Fig. 12). In tennis, because the user hits the ball many times within a short period of time, a haptic proxy must be able to provide impact sensations at a high frequency. When the user's racket comes into contact with the ball, Unident changes its rotational inertia by moving the weight module. Then, the user experiences an impact sensation based on the haptic feedback of Unident. The NPC hits the ball at a random speed each time, and according to this speed, the position at which the weight module stops is determined. We designed this position of the weight module by utilizing the perception model built in the second experiment. Considering that the momentum of the ball determines the magnitude of the impact sensation, the perception model can be applicable even when the speed of the ball is changed as the visual information. We expect that the user perceives an impact sensation with an appropriate magnitude depending on the ball speed.

User Study

We conducted a user study based on the developed application to evaluate the performance of Unident. For this study, 8 paid participants (all males) aged 21 to 25 years (mean: 23.3; SD: 1.69) were recruited. All the participants were right-handed. Each participant received an Amazon gift card worth approximately 9 USD (¥1,000) for their participation in the user study.

Design and Procedure

The participants played tennis with the NPC while holding a haptic proxy and wearing an HMD (HTC VIVE Pro). We prepared two haptic proxies: Unident and VIVE Controller. VIVE Controller provided haptic feedback through vibration when the racket and the ball collided. The NPC hit the ball at a random speed each time. The bal speeds were 0.50, 0.66, 1.00, 1.50, and 2.00, with the standard stimulus being 1. We changed the feedback magnitude of the haptic proxies depending on the ball speed. VIVE Controller determined the vibration intensity in proportion to the speed. In contrast, Unident determined the amount of its rotational inertia to be changed by using the derived perception model. We returned the weight module to its initial position 100 ms after hitting the ball to provide the next impact sensation.

Moreover, we expected that Unident can also render handheld objects of various sizes depending on the initial position of the weight module, such as the weight-shifting proxy [22,36]. To evaluate this ability of Unident, we used three different racket sizes. The initial position of the weight module was set at 0 mm for the

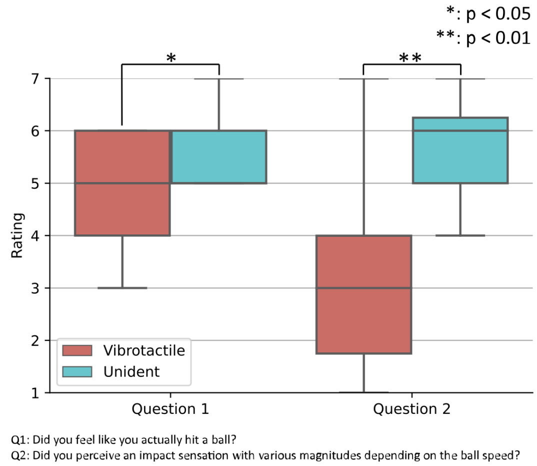

Figure 13: Participants' subjective evaluations for the questionnaires. Question 1 is "Did you feel like you actually hit a ball?". Question 2 is "Did you perceive an impact sensation with various magnitudes depending on the ball speed?".

small size, 35 mm for the medium size, and 70 mm for the large size.

After the participants played tennis with each haptic proxy, they answered the following questions on a 7-point Likert scale.

Q1 Did you feel like you actually hit a ball?

Q2 Did you perceive an impact sensation with various magnitudes depending on the ball speed?

Q3 Did you perceive the difference of the racket size?

Results and Discussion

Fig. 13 shows the results of the first two questions related to the impact sensation. Wilcoxon signed-rank tests indicated significant differences for both questions: Q1 ($W = 48, p = 0.0249$) and Q2 ($W = 0, p = 0.000034$). The results indicate that Unident can provide a more realistic impact sensation than vibrotactile feedback, even when the users swing it at different speeds. Moreover, for the last question related to the racket size, the participants all responded with a high rating of ≥ 5 out of 7 (mean: 5.88). These results indicate that Unident can provide impact sensations with various magnitudes applied to a handheld object and the size of the handheld object in a VR application.

We received notable comments about the performance of Unident for providing an impact sensation. P1, P3, P5, and P7 said, "*I felt a more realistic impact sensation when hitting the ball with Unident.*" P2 said, "*The impact sensation on the larger racket felt smaller than I expected.*" We presume that this is because the amount of the rotational inertia that could be changed was smaller because the initial position of the weight module was increased to render the larger racket. To solve this problem, for example, we can separate the weights for size rendering from those for providing an impact sensation. P4, P6, and P7 said, "*When I swung the racket faster, the haptic feedback of Unident felt slow*". According to this comment, we understand that as the speed at which users swing the handheld object increases, the performance of Unident for providing impact sensations is degraded owing to the actuation speed of the weight module. We will discuss this limitation in detail in the next section. In addition, we returned the weight module to its initial position after providing impact sensations, but no comments mentioned the negative effect of returning the weight module.

8 Future Work and Limitation

Faster Change of the Rotational Inertia

According to our model, Unident must change its rotational inertia within the amount of time taken for the impact force to be actually applied to a handheld object. Although an actual impact force applied to the handheld object takes approximately 1-7 ms [6, 7], Unident takes 150 ms to change its rotational inertia. No comments about this time difference were received in the two experiments where the users swung Unident at a fixed speed, but three users mentioned the time difference in the user study where the users swung it freely. This suggests that as a user's swing speed increases, this time difference is likely to affect the performance of Unident more significantly. To solve this problem, Unident requires a more rapid change in its rotational inertia. Considering that the rotational inertia is proportional to the first power of the mass and the second power of the distance from the holding point, enhancing the motor performance is a more efficient approach than making the weight module heavier. We can also spread its surface at a high speed instead of moving the weight [14, 37].

Timing of Motor Actuation

Some comments were received regarding the timing of the motor actuation in the experiment, such as the followings:

> - *I felt like the timing of the visual information and haptic feedback were off.* (Experiment 1)
> - *I felt like the magnitude of the impact sensation changed with each swing under the same conditions. It seemed to be affected by the timing of swinging the handheld proxy.* (Experiment 2)

These comments indicate that the command for actuating the motor must be sent at the correct time to provide an impact sensation using Unident. We will investigate the most appropriate timing for sending the command to provide an impact sensation and the acceptance range of the lag in user studies.

Reality of Unident's Haptic Feedback

In the first experiment, the participants rated Unident's haptic feedback as realistic. However, the visual information was different between the real and virtual environments, which might affect the participants' swing motions or perception. We need to conduct experiments in which participants hit the real ball in the VE to investigate the effect of the visual information.

Moreover, although we found that Unident provided more realistic impact sensations than VIVE Controller, we will investigate further whether Unident can provide more realistic impact sensations than previous force feedback proxies as a future study.

9 Conclusion

We proposed Unident, the handheld proxy for providing users with impact sensations by changing its rotational inertia while users are swinging it. We first derived the kinetic model of how Unident provide an impact sensation on a handheld object, and then conducted two experiments to evaluate the ability of Unident. In the first experiment, we demonstrated that Unident could physically provide an impact sensation by analyzing the pressure on a user's palm. The second experiment showed that Unident could provide an impact sensation with various magnitudes depending on the amount of rotational inertia to be changed. Finally, we developed a VR tennis application and a user study, which indicated that Unident can provide a more realistic impact sensation than vibrotactile feedback and can render the size of handheld objects.

Acknowledgments

We would like to thank Yuto Nishizawa and Ryota Ito for developing applications.

References

[1] M. Achibet, A. Girard, A. Talvas, M. Marchal, and A. Lécuyer. Elastic-arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. In *2015 IEEE Virtual Reality (VR)*, pp. 63–68, 2015. doi: 10.1109/VR.2015.7223325

[2] H. Ando, K. Obana, M. Sugimoto, and T. Maeda. A wearable force display based on brake change in angular momentum. *Proc Artificial Reality and Telexistence 2002*, pp. 16–21, 2002.

[3] M. Antolini, M. Bordegoni, and U. Cugini. A haptic direction indicator using the gyro effect. In *2011 IEEE World Haptics Conference*, pp. 251–256, 2011. doi: 10.1109/WHC.2011.5945494

[4] S. Cai, P. Ke, T. Narumi, and K. Zhu. Thermairglove: A pneumatic glove for thermal perception and material identification in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 248–257, 2020. doi: 10.1109/VR46266.2020.00044

[5] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, p. 119–130. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3126594.3126599

[6] Y. Fujimoto, C. Liu, T. Uesugi, Y. Tanaka, and E. Shintaku. Pipe surface sensor for impulsive force measurement. *TRANSACTIONS OF THE JAPAN SOCIETY OF MECHANICAL ENGINEERS Series C*, 79:1949–1959, 01 2013. doi: 10.1299/kikaic.79.1949

[7] Y. Fujimoto, E. Shintaku, Y. Tanaka, and J. Fujiyoshi. Pad type compressive force sensor suitable for high-speed impact force measurement. *TRANSACTIONS OF THE JAPAN SOCIETY OF MECHANICAL ENGINEERS Series C*, 78:2438–2449, 01 2012. doi: 10.1299/kikaic.78.2438

[8] E. Fujinawa, S. Yoshida, Y. Koyama, T. Narumi, T. Tanikawa, and M. Hirose. Computational design of hand-held vr controllers using haptic shape illusion. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, VRST '17. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3139131.3139160

[9] S. Heo, C. Chung, G. Lee, and D. Wigdor. Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, p. 1–11. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3173574.3174099

[10] S. Je, M. J. Kim, W. Lee, B. Lee, X.-D. Yang, P. Lopes, and A. Bianchi. Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2d plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, p. 763–775. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3332165.3347926

[11] S. Je, H. Lee, M. J. Kim, and A. Bianchi. Wind-blaster: A wearable propeller-based prototype that provides ungrounded force-feedback. In *ACM SIGGRAPH 2018 Emerging Technologies*, SIGGRAPH '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3214907.3214915

[12] D. Koga and T. Itagaki. Virtual chanbara. In *ACM SIGGRAPH 2002 Conference Abstracts and Applications*, SIGGRAPH '02, p. 83. Association for Computing Machinery, New York, NY, USA, 2002. doi: 10.1145/1242073.1242118

[13] R. Kovacs, E. Ofek, M. Gonzalez Franco, A. F. Siu, S. Marwecki, C. Holz, and M. Sinclair. Haptic pivot: On-demand handhelds in vr. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, p. 1046–1059. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3379337.3415854

[14] Y. Liu, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose. Shapesense: A 2d shape rendering vr device with moving surfaces that controls mass properties and air resistance. In *ACM SIGGRAPH 2019 Emerging Technologies*, SIGGRAPH '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3305367.3327991

[15] P. Lopes, A. Ion, and P. Baudisch. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, p. 11–19. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2807442.2807443

[16] K. Minamizawa, H. Kajimoto, N. Kawakami, and S. Tachi. A wearable haptic display to present the gravity sensation - preliminary observations and device design. In *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, pp. 133–138, 2007. doi: 10.1109/WHC.2007.15

[17] N. Nakamura and Y. Fukui. An innovative non-grounding haptic interface'gyrocubesensuous' displaying illusion sensation of push, pull and lift. In *ACM SIGGRAPH 2005 Posters*, pp. 92–es. 2005.

[18] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein. Reality-based models for vibration feedback in virtual environments. *IEEE/ASME Transactions on Mechatronics*, 6(3):245–252, 2001. doi: 10.1109/3516.951362

[19] N. Ryu, W. Lee, M. J. Kim, and A. Bianchi. Elastick: A handheld variable stiffness display for rendering dynamic haptic response of flexible object. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, UIST '20, p. 1035–1045. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3379337.3415862

[20] M. Sakai, Y. Fukui, and N. Nakamura. Effective output patterns for torque display'gyrocube'. In *Online Proceeding of the 13th International Conference on Artificial Reality and Telexistence, December 3-5, 2003, Keio University, Tokyo, Japan*, 2003.

[21] T. Sasaki, R. S. Hartanto, K.-H. Liu, K. Tsuchiya, A. Hiyama, and M. Inami. Leviopole: Mid-air haptic interactions using multirotor. In *ACM SIGGRAPH 2018 Emerging Technologies*, SIGGRAPH '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3214907.3214913

[22] J. Shigeyama, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose. Transcalibur: A weight shifting virtual reality controller for 2d shape rendering based on computational perception model. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–11. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300241

[23] A. F. Siu, E. J. Gonzalez, S. Yuan, J. B. Ginsberg, and S. Follmer. *ShapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction*, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2018.

[24] H. Y. Solomon and M. T. Turvey. Haptically perceiving the distances reachable with hand-held objects. *Journal of experimental psychology: Human perception and performance*, 14(3):404, 1988.

[25] Y. Suzuki, M. Kobayashi, and S. Ishibashi. Design of force feedback utilizing air pressure toward untethered human interface. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '02, p. 808–809. Association for Computing Machinery, New York, NY, USA, 2002. doi: 10.1145/506443.506608

[26] S.-Y. Teng, T.-S. Kuo, C. Wang, C.-h. Chiang, D.-Y. Huang, L. Chan, and B.-Y. Chen. Pupop: Pop-up prop on palm for virtual reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, p. 5–17. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3242587.3242628

[27] H.-R. Tsai and B.-Y. Chen. Elastimpact: 2.5d multilevel instant impact using elasticity on head-mounted displays. UIST '19, p. 429–437. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3332165.3347931

[28] H.-R. Tsai, C.-W. Hung, T.-C. Wu, and B.-Y. Chen. Elastoscillation: 3d multilevel force feedback for damped oscillation on vr controllers. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376408

[29] H.-R. Tsai, J. Rekimoto, and B.-Y. Chen. Elasticvr: Providing multilevel continuously-changing resistive force and instant impact using

elasticity for vr. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–10. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300450

[30] M. Turvey, G. Burton, C. C. Pagano, H. Y. Solomon, and S. Runeson. Role of the inertia tensor in perceiving object orientation by dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance*, 18(3):714, 1992.

[31] J. M. Walker, M. Raitor, A. Mallery, H. Culbertson, P. Stolka, and A. M. Okamura. A dual-flywheel ungrounded haptic feedback system provides single-axis moment pulses for clear direction signals. In *2016 IEEE Haptics Symposium (HAPTICS)*, pp. 7–13, 2016. doi: 10.1109/HAPTICS.2016.7463148

[32] R. Wettach, C. Behrens, A. Danielsson, and T. Ness. A thermal information display for mobile applications. In *Proceedings of the 9th International Conference on Human Computer Interaction with Mobile Devices and Services*, MobileHCI '07, p. 182–185. Association for Computing Machinery, New York, NY, USA, 2007. doi: 10.1145/1377999.1378004

[33] K. N. Winfree, J. Gewirtz, T. Mather, J. Fiene, and K. J. Kuchenbecker. A high fidelity ungrounded torque feedback device: The itorqu 2.0. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 261–266, 2009. doi: 10.1109/WHC.2009.4810866

[34] K. N. Winfree, J. M. Romano, J. Gewirtz, and K. J. Kuchenbecker. Control of a high fidelity ungrounded torque feedback device: The itorqu 2.1. In *2010 IEEE International Conference on Robotics and Automation*, pp. 1347–1352, 2010. doi: 10.1109/ROBOT.2010.5509485

[35] S. Yoshida, Y. Sun, and H. Kuzuoka. Pocopo: Handheld pin-based shape display for haptic rendering in virtual reality. CHI '20, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376358

[36] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1285–1294, 2017. doi: 10.1109/TVCG.2017.2656978

[37] A. Zenner and A. Krüger. Drag:on: A virtual reality controller providing haptic feedback based on drag and weight shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300441